Journal of Cleaner Production 182 (2018) 705–716

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Review

Marginal abatement cost curves for agricultural climate policy: State-of-the art, lessons learnt and future potential

Vera Eory [a, *], Sylvain Pellerin [b], Gema Carmona Garcia [c], Heikki Lehtonen [d], Ieva Licite [e], Hanna Mattila [f], Thøger Lund-Sørensen [g], John Muldowney [h], Dina Popluga [i], Lisbeth Strandmark [g], Rogier Schulte [j]

[a] Land Economy, Environment & Society, Scotland's Rural College (SRUC), Peter Wilson Building, King's Buildings, West Mains Road, Edinburgh EH9 3JG, UK
[b] INRA, Bordeaux Sciences Agro, Univ. Bordeaux, 33882, Villenave d'Ornon, France
[c] European Commission, Joint Research Centre (JRC), Directorate for Sustainable Resources. Via Enrico Fermi 2749, I-21027 Ispra (VA), Italy
[d] Natural Resources Institute Finland (Luke), Economics and Society, Latokartanonkaari 9, FI-00790 Helsinki, Finland
[e] Ministry of Agriculture of Latvia, Republikas Laukums 2, Centra Rajons, Riga, LV-1010, Latvia
[f] Finnish Innovation Fund, SITRA, Itämerenkatu 11-13, PO Box 160, FI-00181, Helsinki, Finland
[g] Danish Ministry of Energy, Utilities and Climate, Stormgade 2-6, DK-1470, Copenhagen, Denmark
[h] Department of Agriculture, Food and the Marine, Agriculture House, Kildare St, Dublin, Ireland
[i] Latvia University of Agriculture, Liela Street 2, Jelgava, LV-3001, Latvia
[j] Farming Systems Ecology Group, Wageningen University and Research, PO Box 430, 6700AK, Wageningen, The Netherlands

ARTICLE INFO

Article history:
Received 10 August 2017
Received in revised form
27 January 2018
Accepted 30 January 2018
Available online 3 February 2018

Keywords:
Agriculture
Greenhouse gas emissions
Marginal abatement cost curves
Methodology

ABSTRACT

Combatting climate change has risen to the top of the international policy discourse. Effective governance necessitates the generation of concise information on the costs-effectiveness of policy instruments aimed at reducing atmospheric greenhouse gas (GHG) emissions. The marginal abatement cost curve (MACC) approach is a framework commonly used to summarise information of potential mitigation effort, and can help in identifying the most cost-effective managerial and technological GHG mitigation options.

Agriculture offers key opportunities to mitigate GHG emissions and utilise carbon (C) sink potentials. Therefore, a number of countries have developed national agricultural MACCs in the last decade. Whilst these MACCs have undoubtedly been catalysers for the information exchange between science and policy, they have also accentuated a range of constraints and limitations. In response, each of the scientific teams developed solutions in an attempt to address one or more of these limitations. These solutions represent 'lessons learned' which are invaluable for the development of future MACCs.

To consolidate and harness this knowledge that has heretofore been dispersed across countries, this paper reviews the engineering agricultural MACCs developed in European countries. We collate the state-of-the-art, review the lessons learnt, and provide a more coherent framework for countries or research groups embarking on a trajectory to develop an agricultural MACC that assesses mitigations both within the farm gate and to the wider bioeconomy. We highlight the contemporary methodological developments, specifically on 1) the emergence of stratified MACCs; 2) accounting for soil carbon sequestration 3) accounting for upstream and downstream emissions; 4) the development of comprehensive cost-calculations; 5) accounting for environmental co-effects and 6) uncertainty analyses. We subsequently discuss how the mitigation potential summarised by MACCs can be incentivised in practice and how this mitigation can be captured in national inventories.

We conclude that the main purpose of engineering MACCs is not necessarily the accurate prediction of the total abatement potential and associated costs, but rather the provision of a coherent forum for the

Abbreviations: CAP, Common Agricultural Policy; FADN, Farm Accountancy Data Network; IPCC-NI, Intergovernmental panel on Climate Change guidelines for national GHG inventories; LCA, Life Cycle Assessment; LULUCF, land use, land use change and forestry; MACC, marginal abatement cost curve.

* Corresponding author.
E-mail address: vera.eory@sruc.ac.uk (V. Eory).

https://doi.org/10.1016/j.jclepro.2018.01.252
0959-6526/© 2018 Elsevier Ltd. All rights reserved.

complex discussions surrounding agricultural GHG mitigation, and to visualise opportunities and low-hanging fruit in a single graphic and manuscript.

© 2018 Elsevier Ltd. All rights reserved.

Contents

1. Introduction 706
2. Main elements of a MACC and key steps of the process 707
2.1. Boundaries of the analysis 707
2.2. Selecting the measures 707
2.3. Collecting and harmonising data 708
2.4. Reference scenario 708
2.5. Interactions 708
3. Lessons learnt from recent and ongoing projects 708
3.1. Stratifying the farm population 708
3.2. Bringing carbon sequestration into the MACC 708
3.3. Considering upstream and downstream emissions 709
3.4. Comprehensive cost calculations 709
3.5. Accounting for positive and negative co-effects 710
3.6. Uncertainty assessment 711
4. Discussion 712
4.1. Policy integration 712
4.1.1. Cost-effectiveness and incentives 712
4.1.2. Policy packages 713
4.1.3. Point of initiative: farmers, supply chain, consumers 713
4.2. Capturing GHG reductions in inventories 714
4.3. Concluding reflections 714
Acknowledgements 714
References 714

1. Introduction

Climate change has become one of the most pressing environmental problems of our day, with governments and intergovernmental bodies increasingly committing themselves politically and financially to mitigate greenhouse gas (GHG) emissions and adapt to the consequences of the changing climate. Financing climate action from national budgets and creating supporting regulatory environment is a political process, which considers key aspects like environmental effectiveness, economic effectiveness, distributional and social impacts and institutional and political feasibility (IPCC, 2014). In this context information on the costs-effectiveness reducing atmospheric GHG concentrations is essential to inform the climate related decision making process.

The marginal abatement cost curve (MACC) approach is one of a number of frameworks used to summarise information of potential mitigation effort (IPCC, 2014), in particular the costs and GHG mitigation benefits of intended actions. MACCs plot the marginal benefits from GHG reduction, and can suggest an economically optimal mitigation level (i.e. where the marginal costs equal the marginal benefits). They can help in identifying the most cost-effective managerial and technological options (mitigation measures, i.e. actions that farmers and land managers can take) to meet GHG emission targets within and between economic sectors and countries and thus help to define an optimal carbon price.

MACCs have been widely used as a way to integrate and communicate scientific and economic evidence to the policy makers. The earliest cost curves were used for energy efficiency assessment (Meier, 1982) and soon they were informing decisions on other policy areas, like air pollution reduction (e.g. Rentz et al., 1994; Cowell and Apsimon, 1998; Gough et al., 1995; Lanigan et al., 2015) and carbon-dioxide emission mitigation (Mills et al., 1991). MACCs were first applied for agricultural GHG emissions in the early 2000's (Schneider, 2000; McCarl and Schneider, 2000) and they soon proliferated.

Three methodologies have emerged for creating MACCs in agriculture (Vermont and De Care, 2010); 1) using market equilibrium models which depict how a bigger region's economy would behave given the mitigation constraints (Schneider et al., 2007; Van Doorslaer et al., 2015) 2) based on microeconomic models where behaviour of the individual farms is modelled to derive the marginal cost of abatement (De Cara et al., 2005) and 3) engineering (also called bottom-up) MACCs. These latter MACCs are built through aggregation of technical data, by compiling information on the costs and mitigation potential of mitigation measures one by one, calculating their average cost-effectiveness and then plotting them according to increasing cost-effectiveness. These MACCs bring together wide ranging information about the individual mitigation measures, well beyond their costs and mitigation potential, and inform mainly sectoral decision makers in designing policies supporting one or a group of mitigation measures (e.g. Scottish Government, 2013; Department of Agriculture, Food and the Marine, 2015).

Agriculture, being a key contributor to anthropogenic GHG emissions (Tubiello et al., 2013) and at the same time offering C sink opportunities (Smith et al., 2013), is an important sector in the mitigation effort. Its role in mitigation is multifaceted as it is linked to food production and the provision of other ecosystem services, and is complicated by the risks of climate change that it is facing itself. Mitigation opportunities in agriculture have been addressed extensively in recent decades regarding their physical effectiveness, agronomic feasibility and socio-economic aspects. One of the first

examples of an assessment of the cost-effectiveness of agricultural mitigation measures focussed on the European Union (EU) (Bates, 2001); this study was part of an economy-wide report on GHG mitigation in the EU (Blok et al., 2001). Global, regional and national MACCs for agriculture have multiplied since (see e.g. a review by Vermont and De Cara, 2010), driven mostly by the requirement of policy makers' to understand and motivate mitigation in agriculture, and enabled by increasing amount of experimental and modelling evidence on the effectiveness of individual mitigation measures.

A number of agricultural engineering GHG MACCs have been published in the last decade. The UK Government commissioned a series of such studies as part of economy wide analyses (Eory et al., 2015; IGER, 2001; MacLeod et al., 2010; Moran et al., 2008). MACCs have also been developed for the agricultural sector in Ireland (Schulte et al., 2012), France (Pellerin et al., 2017), the United States (Biggar et al., 2013), New Zealand (Pape et al., 2008), China (Wang et al., 2014) and for the dairy sector in the Netherlands (van den Pol-van Dasselaar et al., 2013), while the Danish and Belgian MACCs address the whole economy (Cornet et al., 2013; Danish Inter-ministerial Working Group, 2013). Denmark is currently updating its MACC concerning the agricultural sector (Dubgaard et al., Pers. Comm.). In Finland, GHG abatement costs have been calculated for many potential measures, while cost estimates have been found to be quite context specific; therefore, uncertainty estimates have been recently reported as integral parts of MACCs (Koljonen et al., 2017). Latvia has been working on a MACC and aims to publish it in the beginning of 2018, however already some preliminary results and research approach has already been published (Naglis-Liepa et al., 2015; Popluga and Naglis-Liepa, 2015; Lenerts et al., 2017).

These MACCs have been catalysers for the information exchange between science and policy. Findings of MACCs have been contributing to national carbon budgets and sector specific policies, and the integrative work has often highlighted key gaps in implementation. The subsequent debates have been driving research and policy action to overcome the implementation gaps, by reducing barriers in the uptake of cost saving measures and improving the national GHG inventories so that they mitigation efforts materialising on the ground can be captured, credited and thus incentivised.

Being a popular and useful tool, MACCs have also invited criticism (Kesicki et al., 2011, 2012; Moran et al., 2011; Vermont and De Care, 2010). The key limitations commonly discussed relate to five broad aspects of the assessment: i) formulation and presentation of assumptions, ii) boundaries of the analysis, iii) representation of costs and non-financial barriers, iv) heterogeneity and uncertainty and v) inclusion or exclusion of co-effects.

Each of the aforementioned national agricultural MACCs has developed solutions in an attempt to address one or more of these limitations. These solutions represent 'lessons learned' which are invaluable for the development of future MACCs. To consolidate and harness this knowledge that has heretofore been dispersed across Europe, a workshop was held in December 2016 in Latvia, attended by representatives of six teams who have developed or are developing national agricultural MACCs and by representatives of countries where this tool has not been used yet. In this paper, we present the findings of the workshop and review the engineering agricultural MACCs developed in European countries. We highlight the contemporary methodological developments and discuss two questions of utmost importance for advancing the implementation of agricultural mitigation: 1) how the mitigation potential summarised by MACCs can be incentivised in practice and 2) how this mitigation can be captured in national inventories?

2. Main elements of a MACC and key steps of the process

Experience of different countries shows that several approaches may be applied to analyses of GHG reduction activities, the choice of methodology being determined by the purpose of the assessment: what kind of emissions are considered, what kind of costs are calculated and what kind of information is available (MacLeod et al., 2015). To date, there has been no single harmonised methodology to generating agricultural MACCs; as a result, the national engineering MACCs examined in this paper show differences in their approach. However, they all share a number of fundamental characteristics.

2.1. Boundaries of the analysis

As national policy instruments, and often part of an economy-wide assessment, most MACCs present the abatement potential that relate to the boundary of the agriculture category in national inventories. This means that they are both spatially bound (limited to within-country emissions) and sectorally bound (limited to agricultural activities, i.e. emissions arising on farms), not quantifying the emissions outside the country of interest or outside the agricultural sector that are associated with the production of inputs or consumption of outputs. However, considering the impacts beyond the defined boundary is necessary to avoid emission leakage (Moran et al., 2011). A qualitative assessment could entail excluding measures which are likely to cause emissions leakage, or a life cycle assessment methodology can be used to expand the system boundaries to include the full cradle-to-grave chain of livestock products, as employed in the Irish MACC (O'Brien et al., 2014).

2.2. Selecting the measures

Construction of engineering MACCs starts with the selection of mitigations measures which will be assessed in the exercise. In the context of meeting the twin objectives of food security and climate change mitigation, a variety of measures may be considered: i) measures that reduce absolute emissions without reducing food production, ii) measures that increase food production without increasing emissions and iii) measures that contribute to enhanced abatement in the wider land use sector through carbon sequestration and/or displacement of fossil fuels.

The few hundred measures that have been suggested for GHG mitigation (see a list of studies e.g. in Frelih-Larsen et al., 2014) are commonly narrowed down to a manageable number of measures for each MACC study. Criteria include relevance to the policy questions, e.g.: Is the measure relevant and applicable in the agricultural system being studied? Are there any substantial negative consequences on productivity or on other environmental or animal welfare goals? Is the measure likely to be acceptable to farmers? To what extent should technical measures with low social acceptability be considered?

The selection also needs to consider the broadness/scale of the measures. Measures can refer to individual management practices (e.g. fertilisation, tillage) or involve systemic transformations of farming systems (e.g. modifications of animal diets with associated transformations of crop rotations and fodder production). They can be described very specifically (e.g. covering slurry tanks with plastic tile floating cover) or very broadly (e.g. manure storage management). Using narrow definitions allows the use of very specific assumptions in the calculations, but requires the inclusion of high-resolution data and a much higher number of measures to cover a significant part of potential mitigation. However, specific definitions support the translation of findings into practical farm

advice, reducing ambiguity around the management changes suggested on farms.

2.3. Collecting and harmonising data

MACCs cover a very broad interdisciplinary area and require a wide range of data from natural and social sciences. Projections about future mitigation potential are inevitably complicated by data gaps and the need to make assumptions. In this context, transparency is crucial, to facilitate both scrutiny and updates of the models (Kesicki and Ekins, 2012); the benefits of establishing a systematic review process for MACCs were emphasised by Moran et al. (2011).

For each measure, three variables must be inferred from the research outcomes in order to compute its potential as a GHG mitigation option: i) its effectiveness in reducing emissions ii) the absolute quantity of emissions that the measure applies to (including where the measure is applicable and how much its uptake can be), and iii) the costs of implementing the measure (including losses or gains in production). Ideally, these variables are directly available in the literature, but in many cases expert judgement is required, particularly in relation to costs and likely uptake or applicability of measures.

MACCs bring together quantitative data that has typically been generated by a wide range of individual studies. As a result, the assumptions underpinning the abatement potential and cost-effectiveness may differ for individual measures. In order to prevent 'internal data conflicts' a MACC requires that the underlying assumptions are harmonised across all measures. Examples include fertilizer application rates, prices of inputs such as fuels and fertilizers, and greenhouse gas emissions associated with the manufacturing of nitrogenous fertilizers (e.g. Schulte and Donnellan, 2012).

2.4. Reference scenario

GHG mitigation is calculated against a reference emission scenario related to a base year or against a projected reference emissions scenario, e.g. for the next 30 years. As agricultural activities (including the autonomous uptake of mitigation measures in absence of incentivisation schemes), prices, and technology change over time, the choice of the reference year is important. Slightly surprisingly, Vermont and De Cara (2010) found a positive significant effect of the baseline year on the abatement potential in a sample of 21 agricultural MACCs. Use of past activity data reduces uncertainty of the estimations. However, policy makers often require estimations of future abatement potentials. In such cases, where prices, uptake, agricultural activity, etc. are projected, it is important to clearly report the underlying assumptions.

2.5. Interactions

Mitigation measures often involve changes that interact on or between farms; for example, increasing the legume content of the grass swards reduces the nitrogen fertilizer requirements and therefore impacts on the mitigation potential on all other measures related to nitrogen fertilisation. Though in the past in some engineering MACCs the measures abatement potential were are added up to calculate the cumulative abatement without considering interactions, the interactions can and should be included in engineering MACCs. This can be done for example by assuming mutually exclusive uptake of the measures (e.g. Beach et al., 2008) or via adjusting the abatement potential of the measures when calculating the cumulative abatement (e.g. Moran et al., 2008; Schulte et al., 2012).

3. Lessons learnt from recent and ongoing projects

3.1. Stratifying the farm population

Temporal and spatial differences (i.e. heterogeneity) in emissions, practices, finances, etc. between farms are rarely captured in engineering MACCs beyond the disaggregation level achieved in national inventory calculations (Kesicki and Strachan, 2011; Moran et al., 2011). MACCs based on micro-economic approaches can represent such heterogeneity (De Cara and Jayet, 2000), but that methodology does not reveal much information about individual measures. Engineering MACCs commonly use estimated average values to describe the sector. One of the few exemptions is the cost-effectiveness analysis of mitigation options in the US agriculture (Biggar et al., 2013), where results are disaggregated by the main US regions and by crop type. Considering that MACCs can be used to help identify where policy interventions can be effective, and start dialogues with stakeholders on the best way to proceed (Van Tilburg et al., 2010), it is important to be cognisant whether average farms also are typical farms, and whether average sectoral data reflect sector heterogeneity. In describing the difference, Louhichi et al. (2010) state that the average farm could be defined as a virtual farm, i.e. not observed in reality. In order to reduce the uncertainty related to heterogeneity, a disaggregated approach, i.e. using data collected from multiple sources and on multiple measures, variables, or farms, can be used.

Latvia is now developing a MACC for the agricultural sector using the disaggregated approach by first defining the typologies of farms (Naglis-Liepa et al., 2015). Cluster analysis was used to characterise farms by production intensity, commodity, economic size and other parameters required by MACC methodology (Bockel et al., 2012), based on statistical data from the Farm Accountancy Data Network (FADN). The cluster analysis identified the following three farm types: intensive indoor fodder based livestock farms; intensive cereal farms; mixed specialization and pasture based livestock farms. To account for farms not represented in the FADN dataset (more than half of the farms in Latvia) two more clusters were added: organic farms and small farms. Overall, the use of disaggregated approach was useful to identify customised GHG mitigation measures for each farm type. It elucidated that the highest potential in mitigation of GHG emissions is associated with large-scale intensive farms.

3.2. Bringing carbon sequestration into the MACC

Many authors have shown that a considerable abatement potential exist for additional carbon storage in agricultural ecosystems (e.g. Zomer et al., 2016; Paustian et al., 2016; Schulte et al., 2016). However, early engineering MACCs have focused exclusively on non-carbon-dioxide emissions from agriculture, even though carbon dioxide (CO_2) emissions from soils and energy use and C sequestration by biomass and soilscan have a significant effect on the total estimated abatement (Vermont and De Cara, 2010). There are several explanations for this initial omission. Land use changes like afforestation or wetland restoration reduce agricultural production and may result in carbon leakage if the reduced production results in proportionally higher imports of feed and food (Schulte et al., 2012). This problem does not exist for land management practices such (e.g. reduced tillage, cover crops, straw return or adding biochar), but for these practices the expected abatement has been considered to be either low in some contexts (if the measure is already widely adopted for instance) or still highly uncertain (see for instance Virto et al., 2012 and Dimassi et al., 2014 about reduced tillage). Furthermore, the expected abatement could not be accounted for under most current

national inventory systems. Indeed, the EU Climate and Energy Framework for 2020 does not consider abatement potential arising from land use, land use change and forestry (LULUCF) other than to ensure debits arising are added to Effort Sharing Decision targets. This is especially the case for measures that involve land management, rather than land use change. The French MACC constituted one of the first attempts to consider a wide range of technical measures targeting additional C storage in agricultural soils and biomass, besides more 'conventional' options addressing nitrous oxide (N_2O) and methane (CH_4) emissions (Pellerin et al., 2017). Measures such as agroforestry, hedges, reduced tillage, cover crops, increased lifespan of temporary grasslands and slight intensification of low productive grasslands were assessed. Despite cautious assumptions on their potential applicability (e.g. for agroforestry it was considered that only 7% of the maximum potential applicability would be reached in 2030) it was shown that measures targeting additional C storage accounted for 31% of the total expected abatement (when calculated under higher tiers than current inventory rules).

Additionally to enhancing soil carbon sequestration direct soil GHG emissions can be reduced. Specifically, reclaimed organic soils that are intensively cultivated can be a significant source of CO_2 and N_2O emissions. In Finland for example, these emissions from cultivated peat soils account for more than half (7.6 Mt) of the total annual agriculture related emissions at national level (Statistics Finland, 2015), even though the spatial extent of these soils is limited to 250,000 ha (12% of the utilised agricultural area).

These emissions can be mitigated by raising the water table and possible production of paludicultural crops (Wichtmann et al., 2016). Raising the water table, combined with afforestation, e.g. downy birch trees (*Betula pubescens*), which can grow even on land with high water table, results in GHG abatement costs between €3.6–8.4 t CO_2e^{-1} (Luke, 2016). However, these costs do not include the value of lost farm subsidy payments (current Common Agricultural Policy (CAP) subsidies are conditional on land being kept in good agricultural condition). Alternative mitigation options for cultivated peat soils exist in the form of land use change from arable cropping to permanent grassland. The estimated cost of GHG abatement in Finland ranges between €6.4–20 t CO_2e^{-1} because it may result in a decrease in feed quality due to weed expansion (Rikkonen, 2015). However, subsidy entitlements are not at risk under this option, making it a competitive and low cost option for extensive livestock farms.

In a recent assessment of options for 'climate-smart land management' for atlantic climates, Schulte et al. (2016) showed that the cost-effectiveness of land use and land management options may be improved if management strategies are customised for contrasting soil types. For example, they found that (partial) rewetting or extensification was the most cost-effective land management option on historically drained peat soils; afforestation was most effective on wet, marginal mineral soils outside NATURA 2000 sites, while technological solutions were most effective on well-drained cambisols. These measures will be included in the forthcoming second iteration of the MACC for Irish agriculture (Lanigan et al., Pers. Comm.).

3.3. Considering upstream and downstream emissions

Almost all MACCs published to date have only considered direct GHG emissions occurring within the farm gate. Although this is consistent with sectoral or national policy-making purposes, this can be misleading at larger scale if proposed mitigation measures in the agricultural sector increase emissions in other sectors or elsewhere in the world. To address this question, O'Brien et al. (2014) compared two calculation methods: (i) the approach proposed by the Intergovernmental panel on Climate Change guidelines for national GHG inventories (IPCC-NI), which only considers on-farm emissions, and the Life Cycle Assessment approach (LCA), which considers all emissions related to a production process, including those occurring upstream and downstream from the farm. For Irish agriculture, the results of the MACCs obtained using these two calculation methods showed, on the one hand, that the choice of methodology hardly changed the ranking of measures in terms of cost-effectiveness. However, the cumulated cost-effective abatement potential computed with the LCA approach was almost double of that computed using the IPCC-NI approach. This means that, in the case of Ireland, only half of the total abatement potential could be captured in the national agricultural inventories, which presents challenges for incentivisation, as it may prove difficult to justify the expenditure of exchequer funds on sectoral measures that cannot be accounted for in the national inventory for that sector. The result also suggests that the majority of measures targeting GHG abatement in the national agricultural sector also impact on emissions in other sectors or countries. This is clearly the case for nitrogen fertilisation: measures that reduce the consumption of nitrogen fertilizer (e.g. increased use of legumes) not only reduce N_2O emissions, but also reduce energy use and GHG emissions occurring upstream from fertilizer manufacturing and transport. However, these latter benefits are commonly accounted for, either in other countries (e.g. where the fertilizer is manufactured), and/or other sectors (such as the energy sector). A similar conclusion was obtained from the French MACC. For most measures, the calculated abatement was similar or higher when using a LCA approach (Pellerin et al., 2017). A methodological challenge associated with the LCA approach is that the C-footprint of agricultural products strongly depends on the whole agro-industrial process and trade relationships in which the farm is embedded, whereas the IPCC-NI approach is easier to perform and more robustly delineated. A MACC based on the IPCC-NI approach, supplemented by estimates of emissions avoided or enhanced, both upstream and downstream, may provide the most pragmatic option.

3.4. Comprehensive cost calculations

Kesicki and Ekins (2012) and MacLeod et al. (2015) emphasise the limitations of cost accounting in engineering MACCs; these MACCs usually only consider the direct technical costs associated with the implementation of a measure and fail to account for opportunity costs, transaction costs and public costs. Both the French and the Danish MACCs explored methodologies and considered some cost elements beyond the technical costs.

A key question when calculating costs of mitigation measures is to decide which costs should be included. Inclusion or exclusion of state subsidies or taxes can considerably alter the calculated cost efficiency of the abatement measures and their ranking. In the French study, exclusion of state subsidies for anaerobic digestion (feed-in tariff for electricity produced using biogas) increased the cost from €17 to €55 t CO_2e^{-1}. Conversely, exclusion of tax exemption on agricultural fuel reduced the cost of measures based on fossil energy savings. For instance, the costs of reduced tillage were reduced from €8 t CO_2e^{-1} under the current tax exemption system (implying a cost to the farmer) to €-13 t CO_2e^{-1} without tax exemption on fuels, which corresponds to a financial benefit for the farmer and thus a win-win measure. In other words: higher energy prices increase the financial returns from reduced tillage.

In addition to the losses and gains for farmers, private and public transaction costs associated with the proposed measures may also

be considered. These "hidden" costs, which are rarely considered, reflect the time that farmers need to obtain technical information about the measure, assess its advantages and drawbacks in the context of his farm, make a decision, get the technical skills and to fill administrative documents required for the receipt of subsidies if any. Fig. 1 illustrates an example from France where the calculated cost of some "win-win" measures (i.e. measures characterized by negative cost) may become positive when private transaction costs are included, explaining why these measures are not readily adopted by farmers (Pellerin et al., 2013).

In the Danish MACC, a policy instrument, e.g. a tax or a subsidy, is linked to each measure. The choice of instrument impacts on the public costs associated with each measure, and additionally on consumer choices (Dubgaard et al., Pers. Comm.). For example, a subsidy to farmers for slurry acidification will add costs to public finances and may require increased taxation. This may reduce disposable income hence incentives to work, which in turn may affect the supply of labour. The Danish MACC accounts for the societal costs arising from these distortionary taxes.

3.5. Accounting for positive and negative co-effects

MACCs are designed to assess the cost-effectiveness of reducing one specific type of externality. As opposed to cost benefit analyses, they have the advantage of quantifying the environmental impact in physical units rather than financial units. Avoiding monetisation prevents the introduction of additional uncertainties to the analysis. On the other hand, this also constrains the analysis to a single impact category, without considering potential co-benefits or trade-offs with other impact categories which may significantly alter the outcomes of the overall cost-effectiveness of a mitigation measure (Glenk and Colombo, 2011; Nemet et al., 2010).

It has been well established that many GHG mitigation measures in agriculture and in the wider land use have significant co-effects, notably on air pollution (mainly NH_3 emissions), diffuse water pollution (nitrate, organic nitrogen and P leaching), biodiversity and human health (Eory et al., 2017). It is possible to model multiple pollutants in integrated models (Amann et al., 2011), or in a series of independent models (Anthony et al., 2008), and this has also been implemented in equilibrium GHG MACCs (Schneider et al., 2007), NH_3 MACCs (Brink et al., 2005) and engineering GHG MACCs (Danish Inter-ministerial Working Group, 2013; Eory et al., 2013). For example, the Danish MACC quantified co-benefits on the basis of either the costs associated with environmental damage and health costs (based on the value of statistical life) or the marginal abatement costs of compliance with binding international environmental obligations. For each measure, the higher of these two costs was used. Examples include prices for air pollution (nitrogen oxides, sulphur dioxide, particulate matter, ammonia), and emission of nitrogen to the aquatic environment. In the forthcoming MACC for the Danish agricultural sector the recreational value of nature will also be included.

For some measures the value of the co-benefits (e.g. reduced emissions of nitrogen compounds), are so high that they outweigh the costs of GHG mitigation, resulting in a negative total abatement cost. In such cases, policy drivers other than GHG mitigation may prove decisive in incentivisation and implementation.

A similar approach was used for the United Kingdom (Eory et al., 2013): however, inclusion of the effects of mitigation measures on nitrate, ammonia, phosphorus and sedimentation only slightly changed the total cumulative abatement potential up to a C price of £34.3 t^{-1} CO_2e. In the lowest damage cost scenario, the abatement potential decreased from 36.7% of the reference emissions without co-effects to 36.4% with co-effects, while it increased to 42.2% using the highest damage cost scenarios.

These advances are supporting joined-up policy making (Scottish Government, 2017), but tend to cover only a limited range of co-effects. Usually neglected are those co-effects that are i) inherently difficult to quantify or monetise (e.g. soil quality, animal welfare, biodiversity), ii) highly dependent on the spatial location of the mitigation (e.g. nitrogen and phosphorus leaching, recreation, biodiversity), iii) where the relationship between the GHG mitigation measures and the co-effects are less well explored (e.g. plant and animal health) and iv) social co-effects (e.g. employment impacts). We recommend that at least, a qualitative consideration of the co-effects should complement MACC analysis in all cases, either as part of the exercise or in a later step in the decision making process.

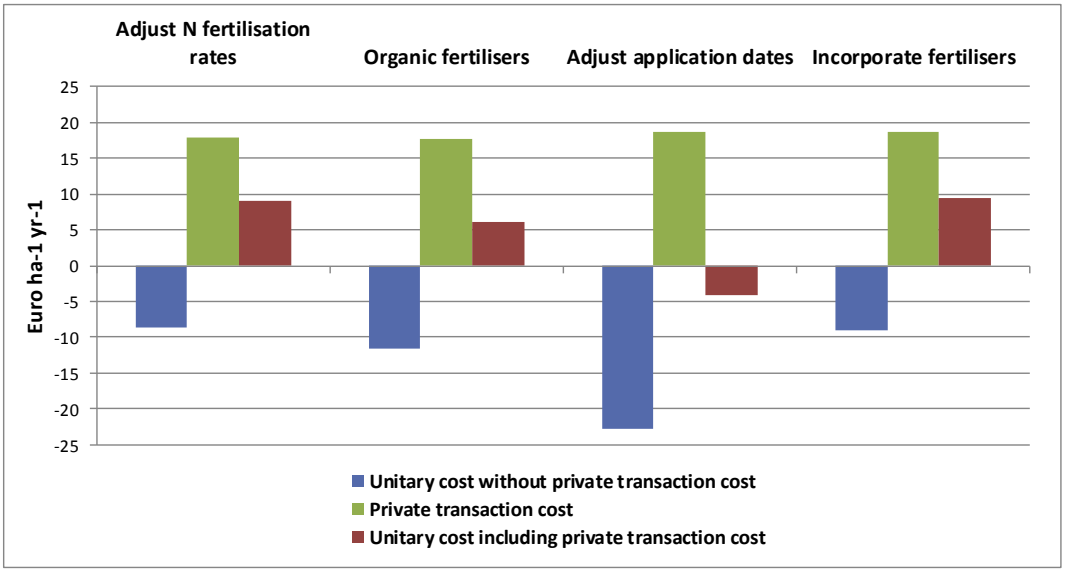

Fig. 1. Calculated cost of four mitigation measures related to nitrogen management including or not private transaction cost (adapted from Bamière et al., 2014). Private transaction costs were calculated according to Mettepenningen et al. (2007).

3.6. Uncertainty assessment

Robust policies that are able to achieve their objectives across a range of possible futures require uncertainties to be explicitly accounted for (Lempert and Schlesinger, 2000). Uncertainty analysis has become part of economic assessments of GHG mitigation, particularly in global, multi-sector models of energy use (Peterson, 2006). Agricultural GHG emission inventories, too, have seen improvements in uncertainty assessments (Milne et al., 2014). However, research on the economics of GHG mitigation in agriculture has rarely included uncertainty analysis, as the heterogeneity of the sector and the spatial and temporal variability of emissions pose particular challenges for uncertainty assessments. It is of concern that MACCs, as highly visual tools conveying complex information, may convey an impression of robustness without explicitly demonstrating the associated uncertainties.

Where information on the uncertainty in the input variables is available, the uncertainty of the output variable can be calculated through Monte Carlo analysis (repeated model runs using a random sampling from the probability distribution of each input variable). Such analysis reveals the uncertainty of the cost-effectiveness and abatement potential of individual mitigation measures, as well as the uncertainty in the total cost-effective abatement. The UK MACC, as used for crop and soil management measures in Scotland, showed that there is up to 54% chance that the real cost-effective abatement potential is only $^{2}/_{3}$ (or less) of the abatement potential estimated by the MACC (Eory et al., in press). The analysis also highlighted that the most important contributors to the uncertainty were the adoption and abatement rates of the measures.

In cases where a full uncertainty analysis is constrained, a sensitivity analysis may be used instead as a quicker option that can still reveal important information about the results, as exemplified by the latest UK MACC, which explored the sensitivity for over 200 input variables (Eory et al., 2015). The sensitivity analysis for cover crops, for example, showed that a reduction in the nitrogen leaching coefficient ($Frac_{LEACH}$) from 45% to 35% reduces the abatement potential of the measure by 19%, while an increase in the seed costs increases its cost-effectiveness by 18%.

Finally, a third approach to accounting for uncertainty involves the generation of scenarios to explore the effect of diverting initial assumptions. For example, the UK MACCs included scenarios on

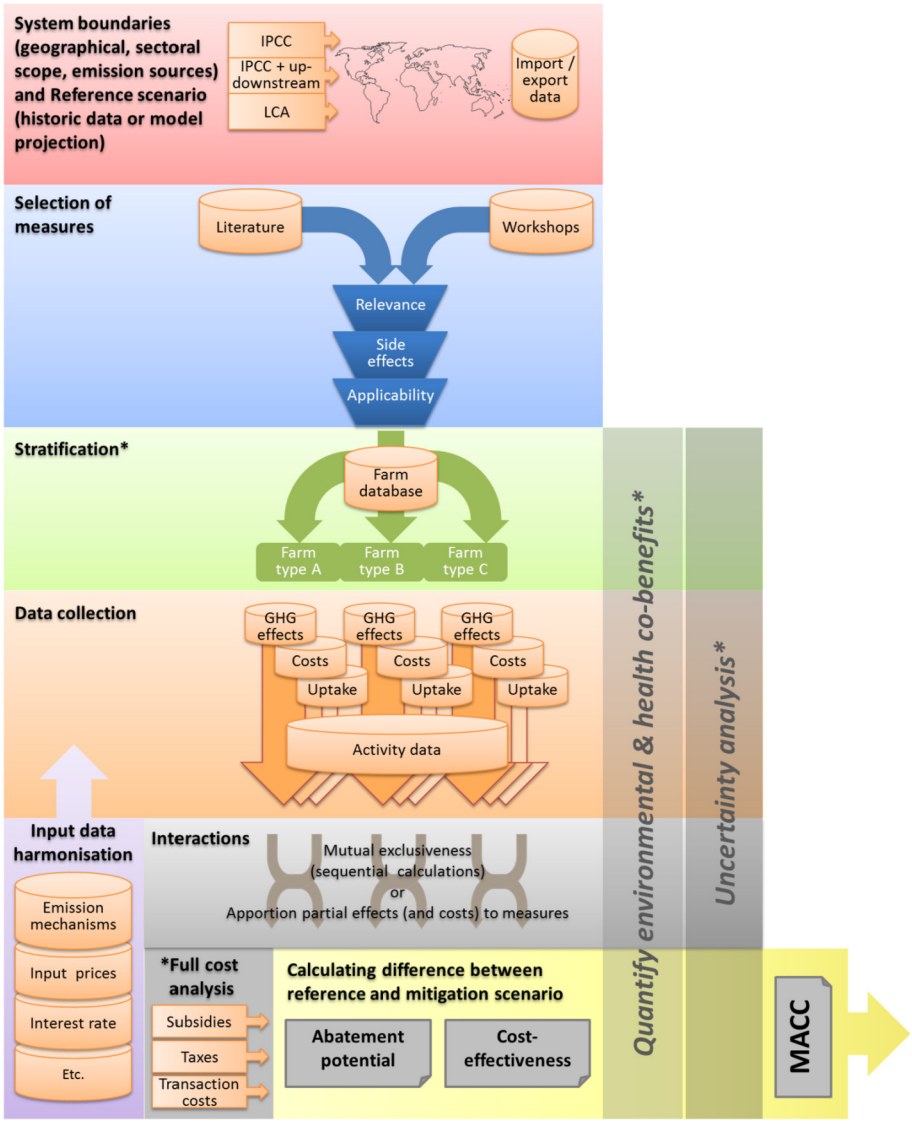

Fig. 2. Steps of constructing national agricultural MACCs (* denotes optional steps).

public and private discount rates, as well as scenarios on low, central and high uptake of individual measures.

As a visual summary of the points above, Fig. 2 provides guidelines on the construction on bottom-up national agricultural MACCs.

4. Discussion

MACCs typically show a 'hypothetical' or technical abatement potential that *could* be reached if all measures to reduce GHG were implemented by all farmers on whose farms measures can be applied, rather than a projection of the magnitude of abatement that is likely to be generated. However, the latter is difficult to estimate in MACC studies, as uptake and application of measures is predominantly dependent on the policies and incentives that MACCs themselves set out to inform. This discrepancy between potential gains and 'making it happen' is also known as the 'think-do-gap' (Schulte et al., 2017). In this section, we assess how policies and inventories can bridge this gap.

4.1. Policy integration

4.1.1. Cost-effectiveness and incentives

A wide range of policy tools is required for the incentivisation of the full variety of mitigation measures, given the differences in cost-effectiveness and types of intervention. Cost-beneficial measures (left-most measures in Fig. 3) cannot currently be incentivised through direct financial support in the EU, as CAP Pillar 2 payments can only be used to compensate farmers for income foregone and additional costs incurred. However, in many cases, adoption of these measures can be incentivised by addressing the information gap that can be behind the low adoption of some of these measures. Examples of such incentivisation include the development of the Carbon Navigator in Ireland; a simple decision support tool that helps farmers identifying opportunities for further gains in efficiency (Murphy et al., 2013). The development of nitrogen fertilisation recommendation systems also falls in this category.

On the other end of the scale (right hand side of Fig. 3) expensive measures are unlikely to be taken up unless direct financial support is provided, both for initial investments and operational costs. Examples of such support may include capital grants, feed-in tariffs and maintenance support.

Cost-neutral measures may neither be incentivised through direct financial supports, since the costs are too low and therefore ineligible (Murphy et al., 2013), nor through information campaigns, since the financial benefits are insufficient to induce change through economic incentivisation alone. For these measures, special attention is given to the potential co-benefits associated with their implementation, to other aspects of environmental or social sustainability. For example, gains in nitrogen efficiency will not only reduce nitrous oxide emissions, but also losses of nitrate and NH_3 emissions, which are regulated under the EU Nitrates Directive (European Commission, 1991) and National Emissions Ceiling Directive (European Commission, 2016a, b), respectively. While such measures may not be cost-effective when considering only the resulting reduction in GHG emissions, this may change when all financial co-benefits are considered, as we have shown in Section 3.5 above. Organisational innovations, such as the establishment of collective anaerobic digesters, may also be incentivised to increase cost-efficiency of these measures and thus fostering their adoption.

Finally, the considerable scope for low-cost carbon storage in soils identified in the French MACC and other national and international studies (e.g. Schulte et al., 2013), has played a leading role for promoting the "4‰ initiative" which was launched during the COP 21 Paris meeting (Ministère de l'agriculture, de l'agroalimentaire et de la forêt, 2015). At the European level, the first pillar of the CAP has introduced the principle of a 'green payment'. Although only modestly ambitious, some of the measures are likely to protect soils and landscape features thus indirectly protecting soil C stocks, such as the protection of permanent pasture, the ban on ploughing in designated areas or the obligation to maintain ecological focus area on at least 5% of the arable area. More recently, the proposed Effort Sharing Regulation under the EU Climate and Energy Framework for 2030 introduces the concept of 'flexibility' to allow Member States to account explicitly for soil carbon changes in meeting their 2030 GHG reduction targets, subject to conditions. This aims to encourage Member States to develop specific measures within their Rural Development Programmes under the second pillar of the CAP. Schulte et al. (2016) developed an early example of a framework for such national policy development, in which they proposed a suite of measures for different soil types and farming systems in Ireland, to either reduce soil carbon emissions, maintain soil carbon stocks, or augment soil carbon sequestration (Fig. 4).

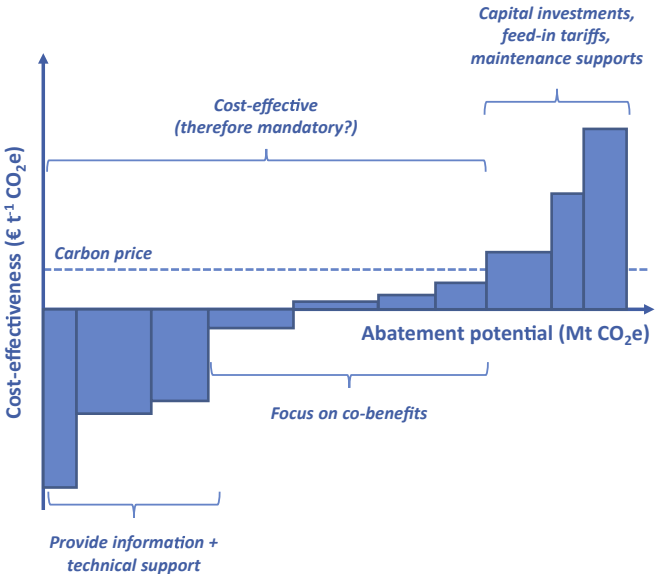

Fig. 3. Relationship between cost-effectiveness and incentivisation.

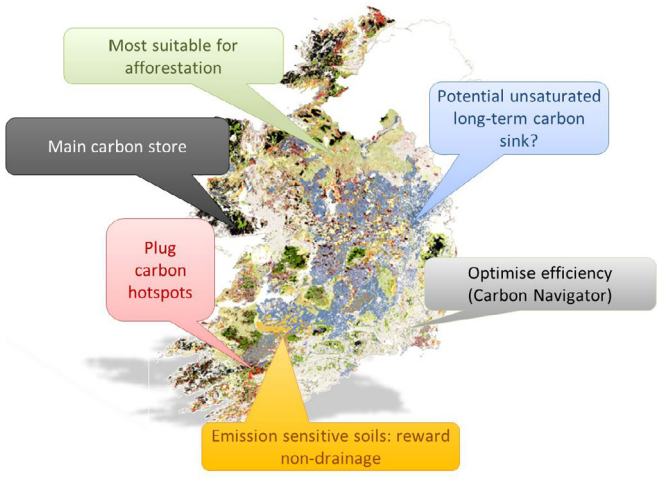
Most suitable for afforestation
Potential unsaturated long-term carbon sink?
Main carbon store
Plug carbon hotspots
Optimise efficiency (Carbon Navigator)
Emission sensitive soils: reward non-drainage

Fig. 4. An example of a national framework for climate-smart land management, where incentives are tailored to soil type and farming systems in order to achieve maximum effectiveness (Schulte et al., 2016).

4.1.2. Policy packages

Implementation of mitigation measures and capitalising on their full potential is more effective when incentives are introduced as support packages that combine aspects of technical, financial and advisory or administrative support.

For example, in France, anaerobic digestion has received a strong support because it is at the crossroad of several strategic public policies (mitigation of climate change, renewable energy, agriculture and rural development). Therefore, the program "Energy, anaerobic digestion and nitrogen autonomy" was launched in 2013 by the French ministry of agriculture, food and forestry and the French Ministry of ecology, sustainable development and energy (Ministère de l'agriculture, de l'agroalimentaire et de la forêt, 2013). The objective is to reach 1000 on-farm anaerobic digesters by 2020 from a base of 90 in 2012. The program includes a combination state subsidies (feed-in tariff for "green electricity" produced from biogas and an annual 33 M€ to support investment), technical support from the French Environment and Energy management Agency (ADEME) and a simplification of administrative procedures (http://www.developpement-durable.gouv.fr/Le-Plan-Energie-Methanisation,32028.html).

Likewise, Scotland has published the draft of its third climate change plan, which details existing and proposed 'policy packages' to support mitigation in all sectors (Scottish Government, 2017). An example is the policy package aimed at reduced emissions from nitrogen fertilizers, which comprise information provision on precision farming, a potential establishment of a national nitrogen target, and the introduction of regular compulsory soil tests. The soil test will at first cover pH, and may, at a later stage, also include phosphorus and potassium tests. Farmers will receive tailored information on opportunities for soil improvement, along with their tests results.

The Irish first National Mitigation Plan, underpinned by national legislation, sets a policy objective of carbon neutrality in the agriculture and land use sector which doesn't compromise sustainable food production. The rolling agri-food strategy process, renewed every five year, (Agri-Food, 2010, Agrivision, 2015, Food Harvest, 2020 and Food Wise, 2025) has been outstandingly successful at engaging the whole sector in the development of a common vision. One example of the policy package in Ireland is the development of a beef data and genomics scheme which aims to improve the carbon efficiency of the suckler beef herd by improving the maternal characteristics of cows selected for breeding. The reliability of this breeding strategy is enhanced by genomically testing the breeding animals. Without correcting the maternal genetic potential, progress would be very slow in achieving the goal of producing a live calf per cow per year. Gathering on-farm data, along with DNA samples builds up a detailed picture of the range of animals in the national herd. The identification of the animals with superior genetic merit for a range of traits ultimately allows for individual farmers to help in driving change at the farm level. Furthermore, this data allows breeding programmes to focus on important long terms goals, such as efficient animals that produce less emissions and products that align with consumer preferences. This livestock improvement requires intimate cooperation between scientists, farmers, the state, and private companies.

4.1.3. Point of initiative: farmers, supply chain, consumers

Traditionally, incentivisation has focussed on farmers as the point of initiative. Experience has learnt that, even in cases where farmers are receptive to discussing climate change, it is difficult to incentivise managerial or technological changes when the benefits of actions by individuals to mitigating global change are difficult to convey. However, it is possible to communicate financial benefits that apply to farm level. In Ireland, this approach led to the development of the aforementioned Carbon Navigator, in which climate change mitigation is treated as a co-benefit to more profitable and efficient farming. The Navigator does not feature technical terminology such as nitrous oxides or methane, instead it lists management criteria that farmers are familiar with such as calving interval and manure use, and for which they can specify their own targets that they feel are within reach given the unique circumstances on their farm.

Whereas farmers cannot be expected to become experts in climate mitigation per se, such expertise is not out of reach for companies further upstream in the value chain. Since many large scale processing companies have shown capacity to recruit specific scientific expertise on GHG mitigation options for their supply base, there is merit in exploring the potential benefits of moving the point of initiative from individual farmers to processors or food companies. Early examples of this include initiatives by Arla (company level) and Origin Green (national level):

The GHG-emissions per litre of produced milk are quite low in Denmark, as milk production per cow is very high. Maintaining a frontrunner position in that regards is generally seen as an important competitive advantage in the Danish dairy sector. Therefore, as a service to their supplies (and owners) the largest Danish dairy cooperative, Arla, conduct free climate checks on dairy farms. This consulting service is aimed at identifying profitable initiatives on the farms, which can also reduce GHG emissions. Similarly, the Danish meat processing company, Danish Crown, is currently doing a project on GHG footprint within major product categories in collaboration with Danish retailers. In Ireland, the Origin Green sustainability programme was launched in June 2012, and has since been adopted by the food and drink sector. As the first national programme of its kind to be rolled out in the world, it capitalises on sustainability as a point of differentiation of Irish food and drink products. At farm level, this translates into sustainability measures being built into 18-monthly inspections, which to date have covered more than 70,000 beef and dairy farms. Similar programmes are currently being rolled out for pigs, poultry, lamb, grain and horticulture. The broadening scope of the farm element of the programme to incorporate water, biodiversity, energy and socio-economic information reflects the ongoing evolution of the programme to ensure that it accounts for potential co-benefits and trade-offs between the various aspects of environmental sustainability.

A third option is to consider consumers as an appropriate point of initiative. A reduction in meat consumption has repeatedly been proposed as an effective approach to reducing GHG emissions. Diet related emissions of UK high meat-eaters were found to be 28%, 54%, 84%, 89% and 149% higher than medium meat-eaters, low meat-eaters, fish-eaters, vegetarians and vegans, respectively (Scarborough et al., 2014). Therefore, decreasing red meat and especially beef consumption and increasing plant protein intake has been seen as a primary or most effective way of decreasing climate impacts of food (Hallström et al., 2015). However, even significant reductions in red meat consumption may have only small effects on agricultural GHG emissions if red meat is substituted by other livestock products such as poultry meat, eggs and dairy products as they also have high GHG emission per kg of digestible protein. For example, Lehtonen and Irz (2013) found unchanged GHG emissions from Finnish agriculture if red meat consumption was reduced by 20%. This result is explained by three main factors: farm subsidies partly coupled to production in less favoured areas, an increase in dairy product consumption and, to a small extent, a decrease in beef imports. .

However, one of the major co-benefits of reduced livestock product consumption can be improved human health (McMichael et al., 2006), though a healthy diet does not necessarily mean lower GHG emissions (Vieux et al., 2012; Tom et al., 2015). "Climate smart" (i.e. sustainable and healthy) diets have many aspects, opportunities and national challenges (collected by e.g. Mattila, 2016), such as biodiversity, eutrophication, acidification and social, cultural and economic dimensions.

4.2. Capturing GHG reductions in inventories

For a mitigation measure to be captured in the national inventories (and therefore "receive credit"), not only it has to be effective but also the effect has to be captured by the estimation methods used by the country. The IPCC general approach to the calculation of emissions for a given emission category is based on two elements: 'activity data' and 'emission factor', where both can be the result of simple measurements, complex calculations or models, or even taken from literature. There are many impediments to the capture of mitigation measures in inventories; including:

- The absence of a specific emission factor: where a new mitigation measure is premedicated on a reduced emission factor, this must be scientifically confirmed in multi-annual experiments, published and approved by the UNFCCC review, before the specific emission factor can be included in the inventory;
- The absence of activity data; whilst some activity can be readily measured or estimated (e.g. national fertilizer consumption), the collection of other activity data such as farm facilities or husbandry practices may require extensive and costly field surveys;
- Incomplete knowledge on the mechanisms underpinning a mitigation measure, and hence its potential synergistic and antagonistic GHG effects at the farm scale;
- The accrual of GHG emission reductions outside the national boundaries, or the sectoral boundaries of the inventory report, like the inter-relatedness of the agricultural and LULUCF inventory which is reflected in the EU Effort Sharing Regulation Proposal (European Commission, 2016b).

From the practical point of view, differentiating activity data and emission factors might not be sufficient to understand whether the effect of a mitigation measure can be measured and reflected in the inventories. Leip et al. (2017) proposed a classification of mitigation measures according to the way they effect emissions into 'mitigation mechanisms' and a distinction between data easily collected from statistics and information requiring experimental measurements or models. This could provide an easy understanding of how much effort is needed for the inclusion of a mitigation measure into a particular emission inventory.

Furthermore, to support aspirations to give full credit to emission reducing activities, activity data and emission factors need to be built in the calculations at a level which allows identifying the changes in agronomic practices rather than only a change in aggregate resource use. For example, if soil nitrous oxide emissions arising from the use of synthetic fertilisers are calculated from aggregate synthetic nitrogen fertilizer use then the emission reduction due to growing more legumes will be reflected in the inventory, but cannot be traced down to the increase in legume growing areas ("blind capture"). On the other hand, disaggregation by crop areas and respective average synthetic nitrogen fertilizer use allows for tracing back the mitigation to legumes ("full capture"). This traceability can be particularly important for policy evaluation.

4.3. Concluding reflections

In this paper, we reviewed a range of trajectories on the development of MACCs in European countries and beyond. While, on hindsight, these trajectories may give the impression of smooth, planned processes, the reality is that many of the MACCs evolved through a process of learning-by-doing. Each faced specific challenges, and developed unique solutions to overcome these challenges. The purpose of this paper, therefore, has been to collate the state-of-the-art, review the lessons learnt, and provide a more coherent framework for countries or research groups embarking on a trajectory to develop an agricultural MACC that assesses mitigations both within the farm gate and to the wider bioeconomy.

As authors and users of agricultural MACCs, we have learnt to appreciate the main purpose of engineering MACCs, which is *not* necessarily the accurate prediction of the total abatement potential and associated costs. Instead, their main purpose is to provide a coherent forum for the extremely complex discussions surrounding agricultural GHG mitigation, and to visualise opportunities and low-hanging fruit in a single graphic and manuscript. Despite their inevitable uncertainties and numerous assumptions, MACCs have proven to be effective levers to build capacity in both research and policy formation. Therefore, the journey of developing a MACC is at least as important as the final product. In this context, their efficacy is maximised when all actors are involved in the development of MACCs from the very start, including both disciplinary and generalist researchers, policy makers, Measurement, Reporting and Verification experts and practitioners.

The extreme complexity of the interactions between the climate and the food system means that it is impossible to account for all possible mitigation measures, interactions or co-benefits, in the development of agricultural MACCs. We therefore recommend that the development trajectories of new MACCs include an *a priori* assessment of the low hanging fruit in their region of interest, to efficiently aid the process of incentivisation and policy formation. This, however, does not imply that assessments should be constrained to those measures that can currently be captured in inventories or incentivised in contemporary policies. As we have seen, policies and inventories can change, in some cases in response to the development of MACCs themselves.

Acknowledgements

The authors gratefully acknowledge the Latvian Ministry of Agriculture for funding and organising the international workshop on the development of agricultural MACCs in Riga, December 2016. This work was also partially supported by the Rural & Environment Science & Analytical Services Division of the Scottish Government, and the Institut National de la Recherche Agronomique.

References

Anthony, S., Duethman, D., Gooday, R., Harris, D., Newell-Price, P., Chadwick, D., Misselbrook, T., 2008. Quantitative Assessment of Scenarios for Managing Trade-off between Economics, Environment and Media, Defra WQ0106 (Module 6), Defra. ADAS, North Wyke Research.

Amann, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Hoglund-Isaksson, L., Klimont, Z., Nguyen, B., Posch, M., Rafaj, P., Sandler, R., Schopp, W., Wagner, F., Winiwarter, W., 2011. Cost-effective control of air quality and greenhouse gases in Europe: modeling and policy applications. Environ. Model. Software 26, 1489–1501.

Bamière, L., De Cara, S., Pardon, L., Pellerin, S., Samson, E., Dupraz, P., 2014. Les coûts de transaction privés sont-ils un obstacle à l'adoption de mesures techniques d'atténuation des émissions de gaz à effet de serre dans le secteur agricole ? Notes et Etudes Socio-Economiques, Ministère de l'agriculture et de la pêche, Service de la statistique et de la prospective, Sous-direction de la prospective et de l'évaluation, pp. 53–71, 2009-, 38.

Bates, J., 2001. Economic Evaluation of Emission Reductions of Nitrous Oxides and Methane in Agriculture in the EU. Bottom-up Analysis. Contribution to a Study

for DG Environment, European Commission by Ecofys Energy and Environment, AEA Technology Environment and National Technical University of Athens. AEA.
Beach, R.H., DeAngelo, B.J., Rose, S., Li, C., Salas, W., DelGrosso, S.J., 2008. Mitigation potential and costs for global agricultural greenhouse gas emissions. Agric. Econ. 38, 109–115.
Biggar, S., Man, D., Moffroid, K., Pape, D., Riley-Gilbert, M., Steele, R., Thompson, V., 2013. Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production within the United States. Report no. AG-3142-P-10–0214. ICF International, U.S. Department of Agriculture Climate Change Program Office, Washington, DC.
Blok, K., de Jager, D., Hendriks, C., 2001. Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change - Summary Report for Policy Makers. European Commission.
Bockel, L., Sutter, P., Touchemoulin, O., Jönsson, M., 2012. Using Marginal Abatement Cost Curves to Realize the Economic Appraisal of Climate Smart Agriculture Policy Pptions. Food and Agriculture Organization of the United Nations, p. 39.
Brink, C., van Ierland, E., Hordijk, L., Kroeze, C., 2005. Cost-effective emission abatement in agriculture in the presence of interrelations: cases for The Netherlands and Europe. Ecol. Econ. 53, 59–74.
Cornet, M., Duerinck, J., Laes, E., Lodewijks, P., Meynaerts, E., Pestiaux, J., Renders, N., Vermuelen, P., 2013. Scenarios for a Low Carbon Belgium by 2050. CLIMACT, VITO.
Cowell, D.A., Apsimon, H.M., 1998. Cost-effective strategies for the abatement of ammonia emissions from European agriculture. Atmos. Environ. 32, 573–580.
Danish Inter-ministerial Working Group, 2013. Catalogue of Danish Climate Change Mitigation Measures - Reduction Potentials and Costs of Climate Change Mitigation Measures. https://bibliotek.dk/da/work/870970-basis:51526953. (Accessed 20 June 2017).
De Cara, S., Jayet, P.A., 2000. Emissions of greenhouse gases from agriculture: the heterogeneity of abatement costs in France. Eur. Rev. Agric. Econ. 27, 281–303.
De Cara, S., Houze, M., Jayet, P.A., 2005. Methane and nitrous oxide emissions from agriculture in the EU: a spatial assessment of sources and abatement costs. Environ. Resour. Econ. 32, 551–583.
Department of Agriculture Food and the Marine, 2015. A Discussion Document on the Potential for Greenhouse Gas (GHG) Mitigation within the Agriculture and Forestry Sector. Irish Government, Department of Agriculture,Food and the Marine, Climate Change and BioEnergy Policy Division.
Dimassi, B., Mary, B., Wylleman, R., Labreuche, J., Couture, D., Piraux, F., Cohan, J.P., 2014. Long-term effect of contrasted tillage and crop management on soil carbon dynamics during 41 years. Agric. Ecosyst. Environ. 188, 134–146.
Eory, V., Topp, C.F.E., Moran, D., 2013. Multiple-pollutant cost-effectiveness of greenhouse gas mitigation measures in the UK agriculture. Environ. Sci. Pol. 27, 55–67.
Eory, V., MacLeod, M., Topp, C.F.E., Rees, R.M., Webb, J., McVittie, A., Wall, E., Brothwick, F., Watson, C., Waterhouse, A., Wiltshire, J., Bell, H., Moran, D., Dewhurst, R.J., 2015. Review and Update of the UK Agriculture MACC to Assess the Abatement Potential for the 5th Carbon Budget Period and to 2050. The Committee on Climate Change.
Eory, V., Allan, G., Bapasola, A., Bealey, W.J., Boyd, I.L., Campbell, J., Colen, L., Glenk, K., Kay, A., MacLeod, M., Moran, D., Moxley, J., Rees, R.M., Sherrington, C., Topp, C.F.E., Watson, C., 2017. Evidence Review of the Potential Wider Impacts of Climate Change Mitigation Options: Agriculture, Forestry, Land Use and Waste Sectors. Scottish Government.
Eory V., Topp C.F.E., Butler A. and Moran D., Addressing uncertainty in efficient mitigaiton of agricultural greenhouse gas emissions, J. Agric. Econ. (in press)
European Commission, 1991. Council directive of 12 December 1991 Concerning the Protection of Waters against Pollution Caused by Nitrates from Agricultural Sources (91/676/EEC). European Commission.
European Commission, 2016a. Directive (EU) 2016/2284 of the European Parliament and of the Council of 14 December 2016 on the Reduction of National Emissions of Certain Atmospheric Pollutants. Amending Directive 2003/35/EC and Repealing Directive 2001/81/EC.
European Commission, 2016b. Proposal for a Regulation of the European Parliament and of the Council on Binding Annual Greenhouse Gas Emission Reductions by Member States from 2021 to 2030 for a Resilient Energy Union and to Meet Commitments under the Paris Agreement and Amending Regulation No 525/2013 of the European Parliament and the Council on a Mechanism for Monitoring and Reporting Greenhouse Gas Emissions and Other Information Relevant to Climate Change. Report No COM(2016) 482 final 2016/0231 (COD). European Commission, Brussels.
Frelih-Larsen, A., MacLeod, M., Osterburg, B., Eory, V., Dooley, E., Katsch, S., Naumann, S., Rees, R.M., Tarsitano, D., Topp, C.F.E., Wolff, A., Metayer, N., Molnar, A., Povellato, A., Bochu, J.L., Lasorella, M.V., Lonhitano, D., 2014. Mainstreaming Climate Change into Rural Development Policy Post 2013. Ecologic Institute, Berlin.
Glenk, K., Colombo, S., 2011. Designing policies to mitigate the agricultural contribution to climate change: an assessment of soil based carbon sequestration and its ancillary effects. Climatic Change 105, 43–66.
Gough, C.A., Chadwick, M.J., Biewald, B., Kuylenstierna, J.C.I., Bailey, P.D., Cinderby, S., 1995. Developing optimal abatement strategies for the effects of sulphur and nitrogen deposition at European scale. Water Air Soil Pollut. 85, 2601–2606.
Hallström, E., C-Kanyama, A., Börjesson, P., 2015. Environmental impact of dietary change: a systematic review. J. Clean. Prod. 91, 1–11.
IGER, 2001. Cost Curve Assessment of Mitigation Options in Greenhouse Gas Emissions from Agriculture. Defra Report CC0229, London.
IPCC, 2014. Climate Change 2014: Mitigation of Climate Change. Working Group III contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Kesicki, F., Ekins, P., 2012. Marginal abatement cost curves: a call for caution. Clim. Pol. 12, 219–236.
Kesicki, F., Strachan, N., 2011. Marginal abatement cost (MAC) curves: confronting theory and practice. Environ. Sci. Pol. 14, 1195–1204.
Koljonen, T., Soimakallio, S., Asikainen, A., Lanki, T., Anttila, P., Hilden, M., Honkatukia, J., Karvosenoja, N., Lehtilä, A., Lehtonen, H., Lindroos, T.J., Regina, K., Salminen, O., Savolahti, M., Siljander, R., Tiittanen, P., 2017. Energia- ja ilmastostrategian vaikutusarviot: Yhteenvetoraportti (in Finniah, with an English abstract, Impact assessments of energy and climate strategy). Publications of the Government's analysis, assessment and research activities 21/2017.
Lanigan, G.L., Donnellan, T., Burchill, W., Forrestal, P., McCutcheon, G., Crosson, P., Murphy, P., Hanrahan, K., Schulte, R., Richards, K., Browne, P., 2015. An Analysis of the Cost of the Abatement of Ammonia Emissions in Irish Agriculture to 2030. Teagasc, Carlow, Ireland.
Lehtonen, H., Irz, X., 2013. Impacts of reducing red meat consumption on agricultural production in Finland. Agric. Food Sci. 22, 356–370. http://ojs.tsv.fi/index.php/AFS/article/view/8007/6412.
Leip, A., Carmona-Garcia, G., Rossi, S., 2017. Mitigation Measures in the Agriculture, Forestry and Other Land Use (AFOLU) Sector. Quantifying Mitigation Effects at the Farm Level and in National Greenhouse Gas Inventories. EUR 28680 EN. Publication Office of the European Union, Luxembourg. https://doi.org/10.2760/51052, JRC107178. ISBN 978-92-79-70516-8.
Lempert, R., Schlesinger, M., 2000. Robust strategies for abating climate change. Climatic Change 45, 387–401.
Lenerts, A., Popluga, D., Rivza, P., 2017. Selection of greenhouse gas emission-reducing measures with analytical hierarchy process approach: a case study from Latvian crop production sector. In: Proceedings of the International Scientific Conference "Economic Science for Rural Development" No.44 "Rural Development and Enterpreneurship. Bioeconomy. Production and Co-operation in Agriculture", pp. 267–273.
Louhichi, K., Janssen, S., Kanellopoulos, A., Li, H., Borkowski, N., Flichman, G., Hengsdijk, H., Zander, P., Fonseca, M.B., Stockstad, G., Athanasiadis, I.N., Rizzoli, A.E., Huber, D., Heckelei, T., van Ittersum, M., 2010. A generic farming system simulator. In: Environmental and Agricultural Modeling: Integrated Approach for Policy. Springer, pp. 109–132.
Luke, 2016. Greenhouse Gas Abatement Calculations on Measures Applicable on Peatlands. (Unpublished Manuscript, Publicly Available March 2017). Natural Resources Institute Finland (Luke).
MacLeod, M., Moran, D., McVittie, A., Rees, R.M., Jones, G., Harris, D., Antony, S., Wall, E., Eory, V., Barnes, A., Topp, C.F.E., Ball, B., Hoad, S., Eory, L., 2010. Review and Update of UK Marginal Abatement Cost Curves for Agriculture. Report no. Report to CCC).
MacLeod, M., Eory, V., Gruere, G., Lankoski, J., 2015. Cost-effectiveness of Greenhouse Gas Mitigation Measures for Agriculture: a Literature Review. Report No OECD Food, Agriculture and Fisheries Papers, No. 89. OECD Publishing, Paris.
McCarl, B., Schneider, U., 2000. U.S. Agriculture's role in a greenhouse gas emission mitigation world: an economic perspective. Rev. Agric. Econ. 22, 134–159.
McMichael, A.J., Powles, J.W., Butler, C.D., Uauy, R., 2006. Food, livestock production, energy, climate change, and health. Lancet 370, 1253–1263.
Mattila, H (toim), 2016. Vähemmän Lihaa. Kohti kestävää Ruokakulttuuria. 223 S. Gaudeamus. ISBN 978-952-495-388-7. Tallinna 2016. www.gaudeamus.fi.
Meier, A.K., 1982. Supply curves of Conserved Energy. PhD Dissertation. University of California, Berkeley, Lawrence Berkeley Laboratory.
Mettepenningen, E., Verspecht, A., Van Huylenbroeck, G., D'Haese, M., Aertsens, J., Vandermeulen, V., 2007. Analysis of Private Transaction Costs Related to Agri Environmental Schemes. ITAES WP6 Consolidated Report, Deliverable N° 15, Document number ITAES WP6 P3D15, Sixth Framework Programme Priority 8 Policy Oriented Research, Specific Targeted Research Project No SSPE-CT-2003–502070, Integrated Tools to Design and Implement Agro environmental Schemes, p. 128.
Ministère de l'agriculture, de l'agroalimentaire et de la forêt, 2015. 4/1000 Initiative: Soils for Food Security and Climate. http://newsroom.unfccc.int/lpaa/agriculture/join-the-41000-initiative-soils-for-food-security-and-climate. (Accessed 19 May 2017).
Ministère de l'agriculture, de l'agroalimentaire et de la forêt, 2013. Le Plan Energie Méthanisation Autonomie Azote (EMAA). http://agriculture.gouv.fr/file/le-plan-energie-methanisation-autonomie-azote-emaa. (Accessed 29 May 2017).
Milne, A.E., Glendining, M.J., Bellamy, P., Misselbrook, T., Gilhespy, S., Rivas Casado, M., Hulin, A., van Oijen, M., Whitmore, A.P., 2014. Analysis of uncertainties in the estimates of nitrous oxide and methane emissions in the UK's greenhouse gas inventory for agriculture. Atmos. Environ. 82, 94–105.
Mills, E., Wilson, D., Johansson, T.B., 1991. Getting started: no-regrets strategies for reducing greenhouse gas emissions. Energy Pol. 19, 526–542.
Moran, D., MacLeod, M., Wall, E., Eory, V., Pajot, G., Matthews, R., McVittie, A., Barnes, A., Rees, R.M., Moxey, A., Williams, A., Smith, P., 2008. UK marginal Abatement Cost Curves for the Agriculture and Land Use, Land-use Change and Forestry Sectors Out to 2022, with Qualitative Analysis of Options to 2050. Report no. RMP4950. Committee on Climate Change. SAC.
Moran, D., MacLeod, M., Wall, E., Eory, V., McVittie, A., Barnes, A., Rees, R.M., Topp, C.F.E., Pajot, G., Matthews, R., Smith, P., Moxey, A., 2011. Developing

carbon budgets for UK agriculture, land-use, land-use change and forestry out to 2022. Climatic Change 105, 529–553.
Murphy, P., Crosson, P., O'Brien, D., Schulte, R.P.O., 2013. The Carbon Navigator – a decision support tool to reduce greenhouse gas emissions from livestock production systems. Animal: Int. J Animal Biosci. 7 (s2), 427–436.
Naglis-Liepa, K., Popluga, D., Rivža, P., 2015. Typology of Latvian agricultural farms in the context of mitigation of agricultural GHG emissions. In: 15th International Multidisciplinary Scientific Geoconference SGEM 2015 "Ecology, Economics, Education and Legislation" Conference Proceedings, vol. II, pp. 513–520.
Nemet, G., Holloway, T., Meier, P., 2010. Implications of incorporating air-quality co-benefits into climate change policymaking. Environ. Res. Lett. 5, 9.
O'Brien, D., Shalloo, L., Crosson, P., Donnellan, T., Farrelly, N., Finnan, J., Hanrahan, K., Lalor, S., Lanigan, G., Thorne, F., Schulte, R., 2014. An evaluation of the effect of greenhouse gas accounting methods on a marginal abatement cost curve for Irish agricultural greenhouse gas emissions. Environ. Sci. Pol. 39, 107–118.
Pape, D., Moffroid, K., Thompson, V., 2008. Analysis of the Potential and Costs for Greenhouse Gas Emission Reductions within the New Zealand Agricultural Sector. ICF International, Ministry of Agriculture and Forestry.
Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.P., Smith, P., 2016. Climate-smart soils. Nature 532, 49–57.
Pellerin, S., Bamiere, L., Angers, D., Beline, F., Benoit, M., Butault, J.P., Chenu, C., Colnenne-David, C., De Cara, S., Delame, N., Dureau, M., Dupraz, P., Faverdin, P., Garcia-Launay, F., Hassouna, M., Henault, C., Jeuffroy, M.H., Klumpp, K., Metay, A., Moran, D., Recous, S., Samson, E., Savini, I., 2013. How Can French Agriculture Contribute to Reducing Greenhouse Gas Emissions? Abatement Potential and Cost of Ten Technical Measures. INRA.
Pellerin, S., Bamiere, L., Angers, D., Beline, F., Benoit, M., Butault, J.P., Chenu, C., Colnenne-David, C., De Cara, S., Delame, N., Dureau, M., Dupraz, P., Faverdin, P., Garcia-Launay, F., Hassouna, M., Henault, C., Jeuffroy, M.H., Klumpp, K., Metay, A., Moran, D., Recous, S., Samson, E., Savini, I., Pardon, L., Chemineau, P., 2017. Identifying cost-competitive greenhouse gas mitigation potential of French agriculture. Environ. Sci. Pol. 77, 130–139.
Peterson, S., 2006. Uncertainty and economic analysis of climate change: a survey of approaches and findings. Environ. Model. Assess. 11, 1–17.
Popluga, D., Naglis-Liepa, K., 2015. Evaluation of measures for mitigation of greenhouse gas emissions suitable for Latvian agriculture. In: 14th International Scientific Conference "Engineering for Rural Development" Proceedings, vol. 14, pp. 584–589.
Rentz, O., Haasis, H.D., Jattke, A., Ruß, P., Wietschel, M., Amann, M., 1994. Influence of energy-supply structure on emission-reduction costs. Energy 19, 641–651.
Rikkonen, P. (Ed.), 2015. Maatalouden energia- ja ilmastopolitiikan suuntia vuoteen 2030 Hillintäkeinojen Analyysi tilatason vaikutuksista ja keinojen hyväksyttävyydestä. Luke 2015. http://urn.fi/URN. ISBN:978-952-326-044-3 accessed: 10/8/2017.
Scarborough, P., Appleby, P.N., Mizdrak, A., Briggs, A.D.M., Travis, R.C., Bradbury, K.E., Key, T.J., 2014. Dietary greenhouse gas emissions of meat-eaters, fish-eaters, vegetarians and vegans in the UK. Climatic Change 125, 179–192.
Schneider, U.A., 2000. Agricultural Sector Analysis on Greenhouse Gas Mitigation in US Agriculture and Forestry, US. Texas A&M University.
Schneider, U.A., Mccarl, B.A., Schmid, E., 2007. Agricultural sector analysis on greenhouse gas mitigation in US agriculture and forestry. Agric. Syst. 94, 128–140.
Schulte, R.P., Crosson, P., Donnellan, T., Farrelly, N., Finnan, J., Lalor, S.T., Lanigan, G., O'Brien, D., Shalloo, L., Thorne, F., 2012. A Marginal Abatement Cost Curve for Irish Agriculture. Teagasc.
Schulte, R.P.O., Donnellan, T., 2012. A Marginal Cost Abatement Curve for Irish Agriculture. Teagasc submission to the public consultation on Climate Policy development. Teagasc, Carlow, 30 April 2012. http://www.teagasc.ie/publications/2012/1186/1186_Marginal_Abatement_Cost_Curve_for_Irish_Agriculture.pdf. Accessed: 10/8/2017.
Schulte, R.P.O., Donnellan, T., Black, K.G., Crosson, P., Farrelly, N., Fealy, R.M., Finnan, J., Lanigan, G., O'Brien, D., O'Kiely, P., Shalloo, L., O'Mara, F., 2013. Carbon Neutrality as a Horizon Point for Irish Agriculture: a Qualitative Appraisal of Potential Pathways to 2050. A report by the Teagasc Working Group on Greenhouse Gas Emissions. Teagasc.
Schulte, R.P.O., O'Sullivan, L., Coyle, C., Farrelly, N., Gutzler, C., Lanigan, G., Torres-Sallan, G., Creamer, R.E., 2016. Exploring climate-smart land management for Atlantic Europe. Agric. Environ. Lett. 1, 160029.
Schulte, R.P.O., Van Apeldoorn, D., Thoorop, R., Bakker, L., O'Sullivan, L., 2017. Bridging the think-do gap on sustainable agriculture. In: 20th Economics for Rural Development Conference. 27–28 April 2017, Jelgava, Latvia.
Scottish Government, 2013. Low Carbon Scotland: Meeting the Emissions Reduction Targets 2013-2027-The Second Report on Proposals and Policies. Scottish Government, Edinburgh.
Scottish Government, 2017. Draft Climate Change Plan - the Draft Third Report on Policies and Proposals 2017-2032. Scottish Government, Edinburgh.
Smith, P., Haberl, H., Popp, A., Erb, K.H., Lauk, C., Harper, R., Tubiello, F.N., de Siqueira Pinto, A., Jafari, M., Sohi, S., Masera, O., Böttcher, H., Berndes, G., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Mbow, C., Ravindranath, N.H., Rice, C.W., Robledo Abad, C., Romanovskaya, A., Sperling, F., Herrero, M., House, J.I., Rose, S., 2013. How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? Glob. Change Biol. 19, 2285–2302.
Statistics Finland, 2015. National Greenhouse Gas Inventory. http://tilastokeskus.fi/til/khki/2015/khki_2015_2016-12-07_tie_001_en.html. Accessed: 10/8/2017.
Tom, M.S., Fischbeck, P.S., Hendrickson, C.T., 2015. Energy use, blue water footprint, and greenhouse gas emissions for current food consumption patterns and dietary recommendations in the US. Environ. Syst. Decis. 36 (1), 92–103.
Tubiello, F.N., Salvatore, M., Rossi, S., Ferrara, S., Fitton, N., Smith, P., 2013. The FAOSTAT database of greenhouse gas emissions from agriculture. Environ. Res. Lett. 8, 015009.
Van den Pol-Dasselaar, A., Blonk, H., Dolman, M., Evers, A., De Haan, M., Reijs, J., Sebek, J., Vellinga, T., Wemmenhove, H., 2013. Cost Effectiveness of Measures to Reduce Greenhouse Gas Emissions in the Dairy Sector (in Dutch). Wageningen University and Research. http://www.rvo.nl/sites/default/files/2013/11/Kosteneffectiviteit%20reductiemaatregelen%20emissie%20broeikasgassen%20zuivel_0.pdf. Accessed: 10/8/2017.
Van Doorslaer, B., Witzke, H.P., Huck, I., Weiss, Franz, Fellmann, T., Salputra, G., Jansson, T., Drabik, D., Leip, A., 2015. An Economic Assessment of GHG Mitigation Policy Options for EU Agriculture. Report no. EUR 27097 EN. European Commission Joint Research Centre Institute for Prospective Technological Studies, Seville.
Van Tilburg, X., Würtenberger, L., Tinoco, R.R., 2010. Policy Brief. Marginal Abatement Cost (MAC) Curve. Energy research Centre of the Netherlands, p. 5. https://www.ecn.nl/docs/library/report/2011/o11017.pdf. Accessed: 10/8/2017.
Vermont, B., De Cara, S., 2010. How costly is mitigation of non-CO_2 greenhouse gas emissions from agriculture?: A meta-analysis. Ecol. Econ. 69, 1373–1386.
Vieux, F., Darmon, N., Touazi, D., Soler, L.G., 2012. Greenhouse gas emissions of self-selected individual diets in France: changing the diet structure or consuming less? Ecol. Econ. 75, 91–101.
Virto, I., Barre, P., Burlot, A., Chenu, C., 2012. Carbon input differences as the main factor explaining the variability in soil organic C storage in no-tilled compared to inversion tilled agrosystems. Biogeochemistry 108, 17–26. https://doi.org/10.1007/s10533-011-9600-4.
Wang, W., Koslowski, F., Nayak, D.R., Smith, P., Saetnan, E., Ju, X., Guo, L., Han, G., de Perthuis, C., Lin, E., Moran, D., 2014. Greenhouse gas mitigation in Chinese agriculture: distinguishing technical and economic potentials. Global Environ. Change 26, 53–62.
Wichtmann, W., Schröder, C., Joosten, H. (Eds.), 2016. Paludiculture – Productive Use of Wet Peatlands. Schweizrbart Science Publishers, p. 272. ISBN 978-3-510-65283-9. Stuttgart 2016.
Zomer, R.J., Neufeldt, H., Xu, J.C., Ahrends, A., Bossio, D., Trabucco, A., van Noordwijk, M., Wang, M.C., 2016. Global tree cover and biomass carbon on agricultural land: the contribution of agroforestry to global and national carbon budgets. Sci. Rep. 6, 12.